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Mathematical Modelling of Stingless Bee Honey Dewatering using Low-Temperature Vacuum Drying with Induced Nucleation Bubbling

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ABSTRACT

Low-temperature vacuum drying with induced nucleation boiling (LTVD-NB) was developed to dewater heat-sensitive materials such as stingless bee honey (SBH). However, its performance can be further optimised to achieve an efficient LTVD-NB operation. The objective of this paper is to investigate the most fitting drying model for dewatering SBH and to develop a suitable mathematical drying model that can be used to predict and optimise dewatering SBH using LTVD-NB. Established experimental data was used to develop the mathematical model. The data result showed that the logarithmic model had the best fit for drying SBH using LTVD-NB as compared to other models based on the highest value of R^2 and the lowest Root mean square, *RMSE* and reduced chi-square, χ^2 values which are 0.999988, 7.87E-05, and 1.41E-08, respectively. The model was further regressed to obtain an optimised mathematical model to better predict an LTVD-NB operation to dewater SBH. In conclusion, an optimised drying model to describe the dewatering process of SBH using the LTVD-NB method was able to be developed based on the multiple regression analysis of the obtained experimental data. Therefore, the drying model can predict the efficiency of this process just by giving the temperature and surface roughness values as input information.

Keywords: Vacuum drying; nucleate boiling; surface roughness; stingless bee honey; temperature

INTRODUCTION

Stingless bee honey (SBH) is known as a highly nutritious substance with various health benefits for human consumption [1]. Even though the industry of stingless bee rearing is still in its infancy stage at this moment, it has the potential to generate up to RM3.03 billion annually if continuous development is done to sustain this industry [2]. There were also efforts to integrate it into the plantation industry such as rubber and palm oil as a value-added element in increasing the revenue of the industry [3][4]. Currently, the oil palm industry is the fourth major contributor to Malaysian revenue in 2020, and with the value-added element of stingless bee rearing in the oil palm industry, the contribution of the industry can be further increased [5]. However, one major issue that keeps causing very serious disruption to the industry is the storage of SBH at room temperature. This has led to major problems in sustaining a stable supply chain in the industry. This is due to its high water content, especially in high-humidity areas such as tropical regions, which promotes a faster fermentation process that leads to carbon dioxide gas pressure building up inside the SBH container. Fermentation of SBH, which is due to high microbial activity in SBH promoted by the presence of high water content, is not favourable because it can reduce the quality of SBH by increasing its sourness and causing its texture to be foamy [6][7]. Therefore, there is a crucial need for the water content in SBH to be reduced to a certain level to avoid the occurrence of fermentation. It was suggested by the Department of Standard Malaysia in 2017 that the ideal condition of SBH should only contain a level of water content of 22% or lower [8].

Typically, the water content is removed via heating, and since SBH is known to be a heat-sensitive material, the dewatering process of SBH must be kept at a low temperature for as short a time as possible so that the quality of SBH can be preserved. Exposure to heat in honey is known to increase the level of hydroxymethylfurfural (HMF) as well as reduce diastase activity [9][10][11]. The occurrence of these two elements can cause a reduction in the quality of the honey, as they are important indicators of the quality of honey [12]. The limit of HMF for honey from tropical ambient temperatures was set to be no more than 80 mg/kg [13]. In addition, exposing honey to heat can cause crystallisation, where the honey turns cloudy and thick, as well as aroma loss, which further deteriorates the honey. That is why honey, especially SBH, should never be heated above 50 °C [14].

By taking into account all these limitations and requirements, low-temperature vacuum drying (LTVD) was considered to be the most suitable method to remove the water content in SBH. The method was also specifically developed to dry or dewater heat-sensitive material, which makes it ideal to handle SBH post-harvest processing due to its low temperature. The water removal can be done at a low temperature, way below the water boiling point, because of the introduction of vacuum conditions to ease the moisture removal process. However, LTVD alone is not sufficient to remove the water content within an acceptable time frame. Hence, LTVD was often coupled with other additional elements, such as the combination of microwave LTVD and vacuum freeze-drying [15][16][17]. Unfortunately, exposure to microwave radiation has the potential to damage the sensitive nutritional content of SBH, whereas the freezing element deteriorates the enzymes in SBH. Thus, these methods are found to be unsuitable for SBH dewatering.

In order to overcome this limitation in dewatering SBH, Ramli et al. developed Low-temperature vacuum drying with induced nucleation boiling (LTVD-NB), which specifically aims to reduce the water content of SBH rapidly without damaging its original nutritional content [18]. This method manipulates the characteristics of the heater's surface roughness to induce a higher rate of nucleation bubbling during the dewatering process, which in turn improves the heat transfer mechanism from the heater into the SBH so that the dewatering process can occur more rapidly. The rougher surface of the heater is estimated to produce a higher amount of nucleation, which in turn increases the rate of drying. This effect is obtained because surface roughness is a parameter that is well known to significantly affect the boiling characteristics of pure substances [19]. The LTVD-NB drying method also enables SBH to be dried at a temperature lower than 50 °C to avoid damaging its nutritional content from excessive heat.

However, the performance of LTVD-NB drying can be further optimised to enhance its efficiency and effectiveness. A common method that is used to optimise a drying process is by developing a mathematical model to predict the performance of the drying process. Up to date, various drying models for various materials, especially agricultural and marine products, have been developed. Unfortunately, drying models for both SBH dewatering and drying using

LTVD-NB have not been developed yet. This is because the method is relatively new in terms of development [20]. Many parameters need to be studied to determine their influence on LTVD-NB's performance. Having a mathematical model to describe and predict the performance of this method will ease researchers in understanding the behaviour of this drying method theoretically, thus accelerating the pace of the research on this topic [21]. Therefore, this paper attempts to investigate the most suitable drying model for dewatering SBH and to develop a suitable mathematical drying model that can be used to predict and optimise the dewatering SBH process using the LTVD-NB method.

EXPERIMENTAL SETUP

The development of a mathematical model for predicting SBH dewatering using LTVD-NB is based on the experimental data obtained from research done by Faeeza et al. (2022) [22]. It is generally known that surface roughness affects the boiling heart transfer process and determines the cavity, whilst temperature controls bubble frequency and heat flux. These impacts on SBH are still being studied, though. The aim of their study was is to examine the effect of temperature and heater's surface roughness on the heat transfer performance and dewatering rate of this method. Based on their experiment, a sample of SBH was dewatered using the LTVD-NB method with a combination of varying temperatures at 40, 45, and 50 °C, coupled with surface roughness of the heater pipe at 0.8, 3.39, 8, and 11.33 µm for 5 minutes. The results of the research are summarised in Figure 1. A one-way Analysis of Variance (ANOVA) was used to statistically analyze the data that had been gathered. To evaluate if there are statistically significant differences between the means of two or more groups, one-way ANOVA is frequently utilized. At $P < 0.05$, the data in this investigation were statistically significant.

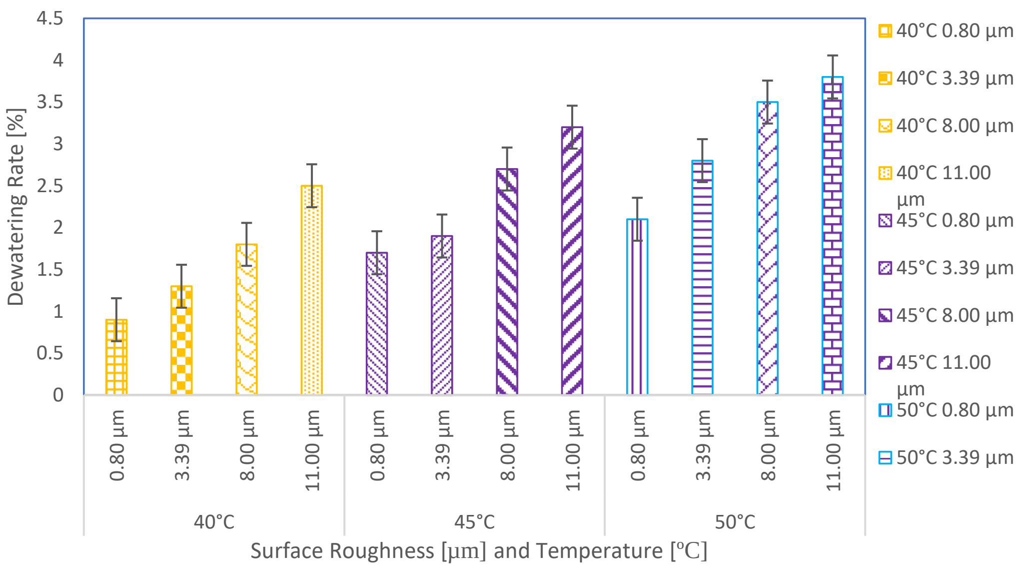

Figure 1. Average water content of SBH after 5 minutes for each surface roughness at different dewatering temperatures

It can be seen that there was a general trend of increasing drying rate when the temperature increased from 40 °C to 50 °C, as well as increasing the surface roughness from 0.8 to 11 µm. The lowest drying rate was achieved with the combination of the lowest surface roughness of 0.8 µm and the lowest drying temperature of 40 °C, with only 0.9% water content reduction.

The highest drying rate of 3.8% water content reduction was achieved by the combination of the highest surface roughness of 11 µm and the highest temperature of 50 °C.

For modeling purposes, the drying performance of each parameter combination was presented in a graph of changes in moisture content against drying time. In this case, the total moisture content evaporated from the honey for each parameter combination was divided into five minutes because of the short drying time. This is due to the limitation of SBH's sensitivity to long exposure to heat. This means that the drying process only occurs during a constant falling rate period. Hence, the moisture change was assumed to occur constantly within those five minutes. Figure 2 shows the performance of each drying parameter combination against drying time for every minute.

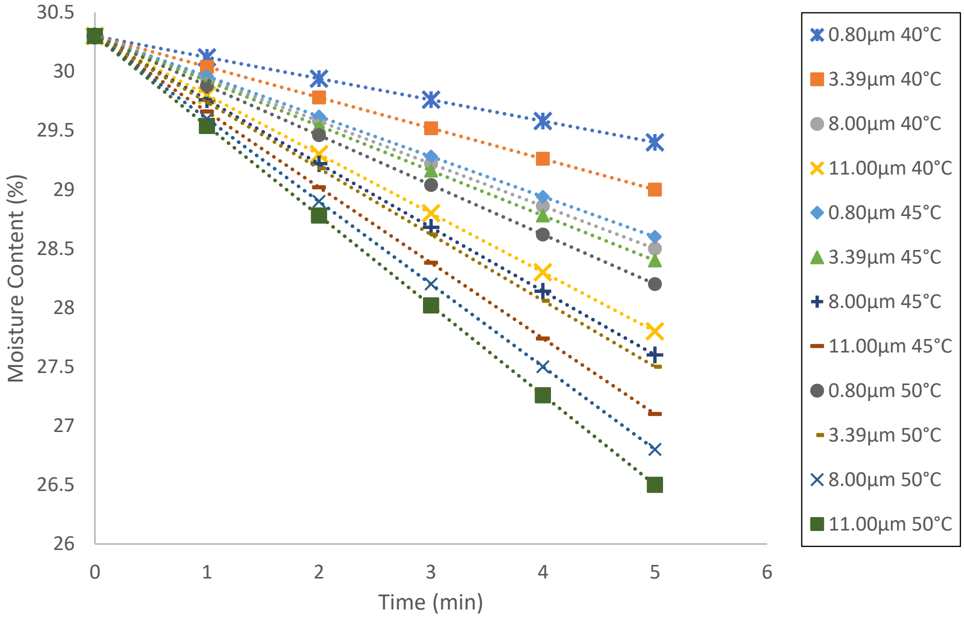

Figure 2. Moisture content variation of surface roughness and temperature parameter combination with drying time.

MATHEMATICAL MODELLING OF SBH DEWATERING

The application of convection drying mathematical modeling is extensively and effectively utilised for various agricultural product drying analyses. To determine the mass transfer equation during the dewatering of SBH, several considerations needed to be taken into account, such as considering the whole process to be isothermal, the mechanism of mass transfer being diffusion in nature, and dewatering SBH being considered a thin layer drying process [23]. The convection drying of SBH in this study only occurred during a constant drying period, and therefore several well-known semi-empirical, as well as empirical models, could be applied to the collected data. Table 1 lists several drying models that can be used to fit the collected data [24].

Table 1. Several drying models

No	Model Name	Model	Reference
1	Midili	MR = exp(-kt)	[25]
2	Newton	MR = exp(-kt)	[26]
3	Page	MR = exp(-kt^n)	[27]
4	Handerson & Pabis	MR = *a*exp(-kt)	[28]
5	Logarithmic	MR = *a*exp(-kt) + c	[29]

The constant *k* is known as drying rate constant, *n* is an empirical parameter that is used to account for non-linearity in the drying method that cannot be precisely described by a simple linear model, *c* is a constant or coefficient in a drying model equation that determines the scale or magnitude of the drying rate and *t* represents the drying time. The fitting of these drying models was done using Microsoft Excel software, while the constants were calculated using the non-linear regression function in IBM SPSS Statistics software and two-way analysis of variance (ANOVA). Bonferroni's test was applied to the data set obtained to ensure that any false-positive results could be avoided. The significant difference value from this test was $p < 0.05$. The experimental data were regressed against five of the most well-known drying models. The water content data of the initial and after dewatering experiments was converted into a water content ratio via Equation 1:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

where *MR* is the water ratio, *M* is the final water content reading in decimal wet basis after the experiment, M_0 is the initial water content of SBH, and M_e is the equilibrium water content in wet basis. In this study, M_e value was too small and therefore approximated to 0. Hence, *MR* was shortened down to M/M_0 instead of following Equation 1 [30]. In this study, the coefficient of determination, R^2, reduced chi-square, χ^2, and the root mean square error, *RMSE*, were used to determine the quality and accuracy of the drying model. R^2 is obtained statistically from the regression analysis, whereas the χ^2 and *RMSE* values are calculated based on Equations (2) and (3). The model that has the lowest reduced χ^2 and RMSE values, as well as the highest R^2 value, will be selected to model the SBH drying.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{3}$$

$MR_{exp,i}$ from the equations is the experimental value of MR obtained from the experiment, $MR_{pre,i}$ is the predicted value of *MR*, *N* is the number of observations, and *n* is the number of constants in the drying model. The R^2, χ^2, and *RMSE* values were also compared with other mathematical drying models from the literature to observe their performance and drying curve behaviour. After that, the relationship between the best mathematical model's constants and the drying parameters, i.e., the heater's surface roughness and temperature, was also determined. The effect was investigated by applying multiple regression combinations of different equations as follows:

Linear: Y = a + bX (4)
Logarithmic: Y = a + b ln (X) (5)
Power: Y = aXb (6)
Exponential: Y = a exp(bX) (7)
Arrhenius: Y = a exp(b/X) (8)

RESULTS AND DISCUSSION

Several drying models were fitted with the drying data of all combinations between the ranges of surface roughness and drying temperature collected from this experiment to determine the value of changes in moisture content against the time taken for the drying process. The performance of each drying model compared to the experimental data was compiled in Table 2, which shows the statistical results of each drying model. It listed all coefficients and constants for each drying model that were obtained through multiple regression analysis.

Table 2. Statistical results of selected drying models.

Drying Model	Surface Roughness (μm)	Temperature (°C)	a	k	n	b	c	R^2	RMSE	χ^2
Midili	0.8	40	1.025	0.025	-0.009	-0.006		0.999988	0.000251	2.02E-07
	3.39	40	1.044	0.043	-0.011	-0.009		0.999975	0.000528	9.08E-07
	8	40	1.059	0.056	-0.017	-0.013		0.999951	0.001022	3.47E-06
	11	40	1.111	0.104	-0.018	-0.018		0.999903	0.001998	1.36E-05
	0.8	45	1.001	0.000	-403.56	-0.012		0.999967	0.000909	2.60E-06
	3.39	45	1.001	0.000	-80.24	-0.013		0.999959	0.00114	4.12E-06
	8	45	1.002	0.001	-79.94	-0.021		0.999901	0.00271	2.42E-05
	11	45	1.003	0.001	-79.82	-0.024		0.999871	0.003538	4.20E-05
	0.8	50	1.001	0.001	-80.18	-0.015		0.999949	0.001398	6.25E-06
	3.39	50	1.002	0.001	-79.97	-0.020		0.999908	0.002521	2.09E-05
	8	50	1.003	0.002	-79.72	-0.026		0.999845	0.004237	6.11E-05
	11	50	1.004	0.002	-79.62	-0.028		0.999817	0.005003	8.64E-05
							Average	**0.999920**	**0.002105**	**2.22E-05**
Newton	0.8	40		0.006				0.999987	6.1E-05	6.84E-09
	3.39	40		0.009				0.999973	0.000128	3.06E-08
	8	40		0.012				0.999948	0.000247	1.17E-07
	11	40		0.017				0.999898	0.000479	4.56E-07
	0.8	45		0.011				0.999954	0.00022	9.21E-08
	3.39	45		0.013				0.999942	0.000275	1.46E-07
	8	45		0.02				0.999861	0.000648	8.49E-07
	11	45		0.023				0.999818	0.000843	1.47E-06
	0.8	50		0.014				0.999929	0.000337	2.21E-07
	3.39	50		0.019				0.999871	0.000603	7.33E-07
	8	50		0.025				0.999782	0.001007	2.12E-06
	11	50		0.027				0.999741	0.001186	2.99E-06

						Average	**0.999892**	**0.000503**	**7.69E-07**
Page	0.8	40		0.006	1.009		0.999998	1.37E-05	1.97E-10
	3.39	40		0.009	1.014		0.999995	2.89E-05	8.90E-10
	8	40		0.012	1.019		0.99999	5.61E-05	3.43E-09
	11	40		0.016	1.027		0.999979	0.00011	1.37E-08
	0.8	45		0.011	1.018		0.999991	4.99E-05	2.70E-09
	3.39	45		0.013	1.020		0.999988	6.27E-05	4.30E-09
	8	45		0.019	1.031		0.999972	0.00015	2.57E-08
	11	45		0.022	1.036		0.999963	0.000196	4.49E-08
	0.8	50		0.014	1.022		0.999986	7.69E-05	6.55E-09
	3.39	50		0.018	1.030		0.999974	0.000139	2.22E-08
	8	50		0.024	1.039		0.999955	0.000235	6.56E-08
	11	50		0.026	1.043		0.999946	0.000278	9.31E-08
						Average	**0.999978**	**0.000116**	**2.36E-08**
Handerson Pabis	0.8	40	1.000	0.006			0.999987	3.01E-05	1.35E-09
	3.39	40	1.000	0.009			0.999973	6.32E-05	6.09E-09
	8	40	1.001	0.012			0.999947	0.000122	2.35E-08
	11	40	1.001	0.017			0.999895	0.00024	9.32E-08
	0.8	45	1.000	0.012			0.999953	0.000109	1.85E-08
	3.39	45	1.001	0.013			0.999941	0.000137	2.94E-08
	8	45	1.001	0.020			0.999856	0.000325	1.75E-07
	11	45	1.002	0.023			0.99981	0.000425	3.05E-07
	0.8	50	1.001	0.014			0.999927	0.000168	4.40E-08
	3.39	50	1.001	0.020			0.999866	0.000303	1.51E-07
	8	50	1.002	0.026			0.999771	0.000509	4.45E-07
	11	50	1.003	0.028			0.999728	0.000601	6.31E-07
						Average	**0.999888**	**0.000253**	**1.92E-06**
Logarithmic	0.8	40	1.155	0.005		-0.155	0.99999	2.61E-05	1.23E-09
	3.39	40	1.431	0.006		-0.431	0.999987	4.4E-05	3.66E-09
	8	40	2.118	0.006		-1.117	0.999989	5.7E-05	6.16E-09
	11	40	2.856	0.006		-1.856	0.999988	8.15E-05	1.27E-08
	0.8	45	1.921	0.006		-0.920	0.999988	5.58E-05	5.09E-09
	3.39	45	2.180	0.006		-1.179	0.999988	6.17E-05	7.18E-09
	8	45	3.143	0.006		-2.142	0.999987	9.98E-05	1.96E-08
	11	45	4.114	0.005		-3.114	0.99999	9.84E-05	1.91E-08
	0.8	50	2.292	0.006		-1.292	0.999987	7.18E-05	1.00E-08
	3.39	50	3.295	0.006		-2.294	0.999989	8.86E-05	1.54E-08
	8	50	3.998	0.006		-2.998	0.999987	0.000121	2.94E-08
	11	50	4.084	0.006		-3.084	0.999986	0.000139	3.93E-08
						Average	**0.999988**	**7.87E-05**	**1.41E-08**

As seen from the statistical results, a very low value of *RMSE* and χ^2, but with a high R^2, were found in all drying models tested. An R^2 value higher than 0.95 is considered a satisfactory fit, which means that all models have good agreement with the experimental data. However, the logarithmic drying model has been shown to obtain the highest R^2, lowest RMSE, and χ^2 values on average, which are 0.999988, 7.87E-05, and 1.41E-08, respectively, compared to other drying models. Therefore, the logarithmic drying model may be assumed to be the best model to accurately describe the drying behaviour of SBH under the influence of nucleation boiling-induced LTVD.

The increase in temperature correlates to the increase in heat energy, which in turn increases the evaporation of water molecules in SBH [31]. The performance of drying increased significantly with the increase in heater surface roughness. Rougher surface roughness induced higher NB due to better heat transfer conditions and promoted a higher rate of water moisture evaporation from SBH [22]. The logarithmic drying model was able to adequately predict the behaviour and performance of SBH drying using LTVD-NB. Therefore, it was confirmed that the Logarithmic mathematical model can be used to describe and predict the behaviour of dewatering SBH using the LTVD-NB method based on the numerical analysis comparison with the experimental data done in this study. In addition, the fitness result of this study was also compared with other drying mathematical models from the literature, and it was found that the Logarithmic model still exhibits the best fit for the drying description and performance prediction.

Based on a comparison between several drying methods, the values of RMSE and χ^2 for this study were found to be very small if compared with other vacuum drying models such as those reported by Ermolaev (2019) due to the short amount of time taken for the drying process compared to the other methods [32]. This was due to the limitation of SBH, which cannot be exposed to heat for long durations to avoid the formation of HMF [33]. Hence, only a short drying period, i.e., 5 minutes drying time was done to the sample of SBH in this study to maintain the quality and original content of SBH. Comparison with other mediums that have a better fit with the logarithmic drying model, such as apricot as reported by Babiker et al. (2016) and tomato juice by Kadam et al. (2011), displayed a high value of R^2 and therefore verified the suitability of the logarithmic model for drying SBH [30][34].

The mathematical drying model for a liquid medium is also very rare in the literature. Thus, the tomato juice drying study by Kadam et al. (2011) served as a good benchmark for a mathematical drying model for liquids such as SBH [34]. Another reason for the suitability of the logarithmic model for predicting SBH drying in LTVD-NB is that this model is based on the assumption that the rate of moisture removal during drying is proportional to the natural logarithm of the difference between the initial and final moisture contents, exactly as stated in the methodology of this study [35]. This model has also been widely used to model the drying of a variety of liquids, including food products, pharmaceuticals, and agricultural products.

Further regression was conducted so that the effect of surface roughness and temperature on the logarithmic model's constants and coefficients could be taken into account by multiple regression analysis. The effects of the experimental conditions on the coefficients and constants are as follows:

$$a = 1.1984 + 0.0997 \cdot SR$$
$$k = 0.0037 \cdot T^{0.6649}$$
$$c = -0.0847 \cdot SR$$

Therefore, the newly developed drying model for SBH dewatering, MR_{opt} is described in Equation 9:

$$MR_{opt} = (1.1984 + 0.0997 \cdot SR) \cdot \exp((-0.0037 \cdot T^{0.6649}) \cdot t) - 0.0847 \cdot SR \quad (9)$$

where SR is the surface roughness, T is temperature, and t is drying time. The most satisfactory model result was shown in Table 3. Figure 4 shows the comparison of experimental MR with predicted MR from the optimised drying model for this study.

Table 3. Effects of surface roughness and temperature on logarithmic model coefficients

Surface Roughness	Temperature	a	k	c	R2	RMSE	χ^2
0.8	40	-0.140	-0.004	1.141	0.9999915	0.000318	0.000939
	45	-0.141	-0.004	1.142	0.9999888	0.000249	0.003252
	50	-0.145	-0.004	1.146	0.999988	0.000222	0.004931
3.39	40	-0.159	-0.004	1.160	0.9999882	0.000464	0.00192
	45	-0.138	-0.005	1.139	0.9999892	0.000412	0.004046
	50	-0.170	-0.004	1.171	0.9999898	0.000327	0.008705
8	40	-0.220	-0.004	1.221	0.9999897	0.001194	0.003635
	45	-0.195	-0.005	1.196	0.9999878	0.001054	0.009326
	50	-0.216	-0.004	1.217	0.9999884	0.000612	0.01432
11	40	-0.281	-0.004	1.282	0.9999891	0.000912	0.00695
	45	-0.256	-0.004	1.257	0.999991	0.000839	0.012046
	50	-0.286	-0.004	1.287	0.9999884	0.000835	0.016783
			Average		**0.9999892**	**0.00062**	**0.007238**

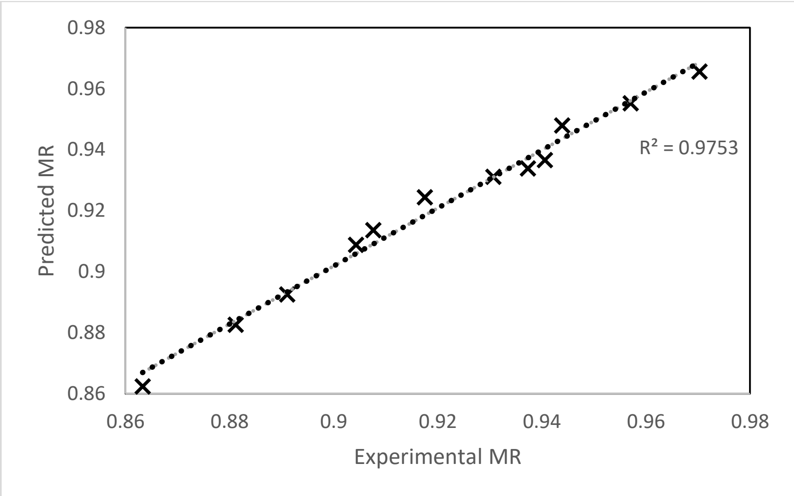

Figure 3. Comparison of experimental MR with predicted MR from optimised drying model.

Figure 3 showed that the drying data obtained by using the optimised mathematical model were spread on a straight line with an R^2 value of 0.9753. This indicated that the predicted and experimental data of dewatering SBH using the LTVD-NB method when applying the optimised mathematical model were in good agreement with one another. It can be assumed that the newly developed mathematical model which was based on the Logarithmic model can describe and predict the performance and behaviour of SBH drying using LTVD-NB when the parameters of surface roughness and temperature are inserted into the model as inputs.

Based on the values summarised in Table 4, the R^2 value changed between 0.9999878 and 0.9999915, the *RMSE* between 0.000222 and 0.001194, and the χ^2 between 0.000939 and

0.016783. The value of R^2 for all parameter combinations was to be on average 0.99990, thus no significant trend could be differentiated. However, the value of RMSE showed a significant trend, whereas the value of χ^2 did not show any significant trend to correlate with the temperature and surface roughness values. The *RMSE* value decreased when the temperature rose for all surface roughness. However, they increased slightly when the surface roughness value increased. This means that the accuracy of the modeling increased with the increasing trend of temperature but decreased with the trend of increasing surface roughness. Nonetheless, the range of increment and decrement values of both R^2 and *RMSE* was small and therefore did not affect the overall accuracy of the drying model in predicting and describing the dewatering process.

CONCLUSIONS

A mathematical drying model to describe and predict the performance and behaviour of dewatering SHB using LTVD-NB needed to be developed so that the research on this topic can be further enhanced as efficiently as possible. A mathematical model for describing and predicting the performance of LTVD-NB for SBH was developed based on the experimental data from Faeeza (2022). From the experimental data, a suitable mathematical model to predict the drying model of SBH using LTVD-NB was proposed using a non-linear regression analysis. It was found that the Logarithmic model was able to produce the best fit to describe SBH drying using induced nucleation LTVD with the highest R^2 (Range from 0.999986 to 0.999990), the lowest *RMSE* (Range from 2.60583E-05 to 0.000138915), and χ^2 (Range from 1.22638E-09 to 3.92549E-08). The highest R^2 with the lowest *RMSE* and χ^2 values were obtained when the experimental data with a parameter combination of 0.8 μm and 40 °C temperature was fitted to the logarithmic model.

Next, the logarithmic model was then regressed further using multiple regression analysis to produce an optimised mathematical model to describe and predict LTVD-NB dewatering of SBH in terms of surface roughness and temperature. With the new model, the input parameters in terms of surface roughness and temperature value can be inserted in the newly developed mathematical drying model and prediction of moisture content value in SBH as the output of the model can be determined successfully and accurately. The new model has the R^2, *RMSE*, and χ^2 values changed between 0.9999878 and 0.9999915, 0.000222 and 0.001194, and 0.000939 and 0.016783, respectively. With a higher value of R^2, it is concluded that the new optimised drying model is more suitable to predict the moisture change during the dewatering of SBH using the LTVD-NB method. With the ability to describe and predict the outcome of SBH moisture content when certain input parameters of temperature and surface roughness were given, the study of LTVD-NB can be further assessed more efficiently.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ahmad Syazwan Ramli: Conceptualization, Methodology, Writing-Original draft preparation. Faeeza Abdul Halim: Data curation, Investigation, Writing-Reviewing and Editing. Luqman

Abdul Halim: Visualization, Supervision, Validation. Firdaus Basrawi and Mohd Azwan Mohd Bakri: Writing- Reviewing and Editing.

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REFERENCES

[1] BERNAMA, "Lindungi kelulut untuk pembangunan lestari dan industri 'super food,'" *Astro Awani*, Jun. 05, 2021.

[2] Bernama, "Industri kelulut mampu capai jualan RM3.03 bilion setahun," *Bernama.com*, 2020. .

[3] M. A. C. Soh, "Stesen penyelidikan MPOB Kluang miliki koleksi germplasma sawit terbesar dunia," *DagangNews.com*, Kuala Lumpur, Apr. 2021.

[4] R. F. Ramadani, R. Raffiudin, N. S. Ariyanti, S. Biagioni, E. Treanore, and H. Behling, "Stingless bee foraging behavior and pollen resource use in oil palm and rubber plantations in Sumatra," *J. Entomol. Indones.*, vol. 18, no. 2, p. 81, 2021.

[5] A. P. GHULAM KADIR, "Oil Palm Economic Performance in Malaysia and R&D Progress in 2020," *J. Oil Palm Res.*, 2021, doi: 10.21894/jopr.2021.0026.

[6] M. Z. Mustafa, N. S. Yaacob, and S. A. Sulaiman, "Reinventing the honey industry: Opportunities of the stingless bee," *Malaysian J. Med. Sci.*, vol. 25, no. 4, pp. 1–5, 2018, doi: 10.21315/mjms2018.25.4.1.

[7] S. S. D. Mohammed, B. Yohanna, J. R. Wartu, N. L. Abubakar, and S. Bello, "Wine Produced From Fermentation of Honey Slurry and Dates Palm Fruit Juice Blend Using Saccharomyces cerevisiae Isolated From Palm Wine," *Int. J. Biol.*, vol. 10, no. 3, p. 52, 2018, doi: 10.5539/ijb.v10n3p52.

[8] "MALAYSIAN STANDARD MS 2683 : 2017," 2019.

[9] Y. Eshete and T. Eshete, "A Review on the Effect of Processing Temperature and Time duration on Commercial Honey Quality," *Madridge J. Food Technol.*, vol. 4, no. 1, pp. 158–162, 2019, doi: 10.18689/mjft-1000124.

[10] S. K. Yap and N. L. Chin, "Kinetic modeling on quality parameters of raw Kelulut honey during dehydration process," *J. Food Process Eng.*, no. February, 2020, doi: 10.1111/jfpe.13392.

[11] A. Jedlińska *et al.*, "The application of dehumidified air in rapeseed and honeydew honey spray drying - Process performance and powders properties considerations," *J. Food Eng.*, vol. 245, pp. 80–87, 2019, doi: 10.1016/j.jfoodeng.2018.10.017.

[12] I. Singh and S. Singh, "Honey moisture reduction and its quality," *J. Food Sci. Technol.*, vol. 55, no. 10, pp. 3861–3871, 2018, doi: 10.1007/s13197-018-3341-5.

[13] Codex Alimentarius Commission, "Codex Alimentarius Commission Standards," *Codex Stan 12-1981*, pp. 1–8, 2001.

[14] N. Jahan, M. A. Islam, F. Alam, S. H. Gan, and M. I. Khalil, "Prolonged heating of honey increases its antioxidant potential but decreases its antimicrobial activity," *African J. Tradit. Complement. Altern. Med.*, vol. 12, no. 4, pp. 134–144, 2015, doi: 10.4314/ajtcam.v12i4.20.

[15] R. L. Monteiro, A. I. Gomide, J. V. Link, B. A. M. Carciofi, and J. B. Laurindo, "Microwave vacuum drying of foods with temperature control by power modulation," *Innov. Food Sci. Emerg. Technol.*, vol. 65, no. March, 2020, doi:

10.1016/j.ifset.2020.102473.
[16] G. Li, Q. Wang, and H. Zhou, "Research on the Application of Vacuum Freeze-drying Technology for Food," *E3S Web Conf.*, vol. 370, pp. 2022–2024, 2023, doi: 10.1051/e3sconf/202337001004.
[17] A. F. Porutchikov and D. P. Trubin, "Low temperature vacuum sublimation refrigerators on carbon dioxide as working fluid," *MATEC Web Conf.*, vol. 324, p. 02004, 2020, doi: 10.1051/matecconf/202032402004.
[18] A. S. Ramli *et al.*, "A new dewatering technique for stingless bees honey," *MATEC Web Conf.*, vol. 131, p. 03014, 2017, doi: 10.1051/matecconf/201713103014.
[19] J. Ham, H. Kim, Y. Shin, and H. Cho, "Experimental investigation of pool boiling characteristics in Al2O3 nanofluid according to surface roughness and concentration," *Int. J. Therm. Sci.*, vol. 114, pp. 86–97, 2017, doi: 10.1016/j.ijthermalsci.2016.12.009.
[20] A. S. Ramli *et al.*, "Experimental analysis on a novel low-temperature vacuum drying with induced nucleation technique for dewatering stingless bees honey," *Dry. Technol.*, vol. 37, no. 2, pp. 149–155, 2019, doi: 10.1080/07373937.2018.1444634.
[21] L. Bennamoun and J. Li, "Drying process of food: fundamental aspects and mathematical modeling," in *Natural and artificial flavoring agents and food dyes*, Elsevier, 2018, pp. 29–82.
[22] F. Abdul Halim, F. Basrawi, A. S. Ramli, A. N. Oumer, and N. A. Azman, "Effect of surface roughness and temperature on the performance of low-temperature vacuum drying with induced nucleation boiling method in dewatering stingless bees honey," *Dry. Technol.*, pp. 1–13, 2022.
[23] C. Ertekin and M. Z. Firat, "A comprehensive review of thin-layer drying models used in agricultural products," *Crit. Rev. Food Sci. Nutr.*, vol. 57, no. 4, pp. 701–717, 2017, doi: 10.1080/10408398.2014.910493.
[24] A. Pujianto, S. D. P. Sidhi, and A. Nurfauzi, "Mathematical Modeling of Thin Layer Drying of Salted Yellowtail Fish Under Open Sun and in Greenhouse Dryer," *Russ. J. Agric. Socio-Economic Sci.*, vol. 91, no. 7, pp. 391–399, 2019, doi: 10.18551/rjoas.2019-07.46.
[25] A. Midilli and H. Kucuk, "Mathematical modeling of thin layer drying of pistachio by using solar energy," *Energy Convers. Manag.*, vol. 44, no. 7, pp. 1111–1122, 2003, doi: 10.1016/S0196-8904(02)00099-7.
[26] A. Ayensu, "Dehydration of food crops using a solar dryer with convective heat flow," *Sol. Energy*, vol. 59, no. 4-6–6 pt 4, pp. 121–126, 1997, doi: 10.1016/S0038-092X(96)00130-2.
[27] V. T. Karathanos and V. G. Belessiotis, "Application of a thin-layer equation to drying data of fresh and semi-dried fruits," *J. Agric. Eng. Res.*, vol. 74, no. 4, pp. 355–361, 1999, doi: 10.1006/jaer.1999.0473.
[28] E. K. Akpinar, Y. Bicer, and C. Yildiz, "Thin layer drying of red pepper," *J. Food Eng.*, vol. 59, no. 1, pp. 99–104, 2003, doi: 10.1016/S0260-8774(02)00425-9.
[29] O. Yaldiz, C. Ertekin, and H. I. Uzun, "Mathematical modeling of thin layer solar drying of sultana grapes," *Energy*, vol. 26, no. 5, pp. 457–465, 2001, doi: 10.1016/S0360-5442(01)00018-4.
[30] A. M. O. A. Babiker, O. E. M. Osman, M. M. Bukhari, E. A. Abdalla, J. N. Ibrahim, and W. Aboshora, "Mathematical Modelling of Thin Layer Solar Drying of Fish (Bagrusbayad)," *Int. J. Multidiscip. Curr. Res.*, vol. 4, no. March, pp. 260–264, 2016, [Online]. Available: http://ijmcr.com.
[31] F. Zhao, Y. Guo, X. Zhou, W. Shi, and G. Yu, "Materials for solar-powered water evaporation," *Nat. Rev. Mater.*, vol. 5, no. 5, pp. 388–401, 2020.
[32] V. A. Ermolaev, "Development of mathematical model for vacuum cheese drying,"

Biointerface Res. Appl. Chem., 2019, [Online]. Available: https://api.semanticscholar.org/CorpusID:243034465.

[33] İ. Önür *et al.*, "Effects of ultrasound and high pressure on physicochemical properties and HMF formation in Turkish honey types," *J. Food Eng.*, vol. 219, pp. 129–136, 2018, doi: 10.1016/j.jfoodeng.2017.09.019.

[34] D. M. Kadam and S. Balasubramanian, "Foam mat drying of tomato juice," *J. Food Process. Preserv.*, vol. 35, no. 4, pp. 488–495, 2011, doi: 10.1111/j.1745-4549.2010.00492.x.

[35] B. Bhandari, "Handbook of Industrial Drying, Edited by AS Mujumdar: CRC Press: Boca Raton, FL; 2015. ISBN: 978-1-4665-9665-8." Taylor & Francis, 2015.